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COMPACT DISC SERVICE LIFE:
AN INVESTIGATION OF THE ESTIMATED SERVICE LIFE OF PRERECORDED COMPACT DISCS (CD-ROM)

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Prepared for the Library of Congress by
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August 2004

Preservation Directorate
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Revised Numbering Scheme

No. 9 - Gibson, Gerald D. ***Preservation of Magnetic Media: A Bibliography. Part I.*** 2001.

No. 10 – Shahani, Chandru J., Youket, Michele H., and Norman Weberg. ***Compact Disc Service Life: An investigation of the Estimated Service Life of Prerecorded Compact Discs (CD-ROM) Held at the Library of Congress.*** 2005

Objective:

It was the objective of this test plan to evaluate the Life Expectancy (LE) of information stored on prerecorded compact discs. For the purposes of this Test Plan, a prerecorded compact disc is considered to be a CD-ROM or a CD-Audio. It does not include recordable CD's (CD-R), rewritable CD's (CD-RW), or DVD's.

The effects of temperature and relative humidity were modeled using a modified Eyring equation. The goodness of fit of the experimental data was compared to four common distributions including Weibull, Lognormal, Normal and Exponential. A lognormal failure time relationship was determined to best describe the distribution of measured or estimated life expectancies. The life expectancy is expressed as the probability of surviving, with a given confidence level, when stored at a prescribed temperature and relative humidity.

Background:

Since their introduction in the early nineteen eighties, there has been much published regarding the suitability of the compact disc to serve as a media for archiving music, art and other information. Most publications offer only anecdotal information. Some offer actual data but at undefined conditions. Fewer yet provide sufficient data to actually allow meaningful disc life expectancies to be determined. Understanding the life expectancies and the factors that influence that life is important for all users and essential for all that need to provide both archival and access to this media format.

The growth of CD media form is unprecedented in any other media format. So prolific has this product become that what was once an expensive means for producing classical music is now available free in magazines and books. It is even mailed unsolicited as an inducement to affiliate with an on-line internet services.

The scale of CD-manufacture is such that it is not economical for production of quantities less than a few hundred. One of the major expenses is the production of an encoded master and injection molding stampers. Set up time requires hours of factory labor and the total time from recording to final CD could range from a few hours up to several days. This requirement, therefore, is conducive to mass production and distribution of inexpensive prerecorded compact discs which constitute the majority of the Library of Congress holdings.

The compact disc format is governed by standards referred to as the Yellow book and the Red book. These standards specify the data layout, dimensions and specific optical properties required in the production of CD-ROM media.

These standards do not place any requirement on the chemical or physical stability of the disc. As such, there are many variations being used in disc manufacture. Differences exist in the stability of the reflector material and the protective lacquer coating. These differences are considered to be significant variables in the permanence of information stored on the compact disc.

This study is designed to serve as a pilot study to provide an estimate of the life expectancy of the information stored at the library of congress.

Applicable Documents:

Life Expectancy of Information stored in Compact Disc Systems, Method for Estimating Based on Effects of Temperature and Relative Humidity, ANSI/NAPM IT9.21-1996

Accelerated Service Life Predictions of Compact Discs, William P. Murray, ASTM STP 1202, 1994

Applied Reliability, P. A. Tobias and D. C. Trindade, Van Nostrand Reinhold, 1986

Ramp Profiles for Optical Disc Incubation, J. J. Wroebel, SPIE Vol. 2338, 1994

Lifetime of Kodak Writable CD and Photo CD media, D. A. Stinson and N. Zaino, SIGCAT DISCourse, Vol 9(1) 1-11, 1995

Optical Disk Accelerated Aging Testing Methodology and Experimental Results, Basil Manns, Library of Congress, August 1990

Definitions

Baseline: The condition representing the disc at the time of manufacture. This is customarily the value of test parameters taken prior to the application of any aging stress. The time designation is usually "t=0" to indicate time equal to zero hours.

Block Error Rate: (BLER) As defined by section 12.5.2 of ISO/IEC 10149, specification of random errors.

Compact Disc – Recordable (CD-ROM): For the purposes of this test plan, a CD-ROM is a disc which has been prerecorded by injection molding and metalization. CD-Audio is included in this definition.

End-of-life: The occurrence of any loss of information. The loss will be determined as the point at which the error correction methods are unable to correct the error within the allotted time for such correction.

F(t): The probability that a random unit drawn form the population fails by time =(t). F(t) is also numerically equal to the fraction of all units in the population which fail by time = (t).

Information: The signal or image recorded using the system.

Life Expectancy: (LE) The length of time that information is predicted to be retrievable in a system under extended term storage conditions.

R(t): The probability that a unit drawn from the population will survive at least time = (t). R(t) is also numerically equal to the fraction of all units in the population which survive at least time = (t).

Retrievability: The ready access to the information recorded on the medium. The access shall be restricted to the manner intended using the prescribed system.

Standardized Life Expectancy (SLE): The minimum life span that one can expect, with 95% confidence, that 95% of the product will attain if stored at a temperature not exceeding 25 °C and a relative humidity not exceeding 50 %.

Stress: The experimental variable to which the specimen is exposed for the duration of the test interval. In this test plan, the stress variables are confined to temperature and relative humidity.

System: A system consists of recording medium, hardware, software, and documentation to retrieve information.

Test cell: The device that controls the experimental environment in which the specimens receive the stress variable.

Test Pattern: The distribution of 1's and 0's within a block.

Usage Stress: The condition that media are likely to experience in normal exposure. For the purposes of this test plan, these conditions are defined as 25 °C (77 °F) and 50 % relative humidity. These conditions are slightly warmer than a normal household or office environment so the life expectancies calculated are correspondingly conservative.

Test Description:

A random sample of 160 prerecorded compact discs was obtained from duplicate within the Library of Congress holdings. One half of the discs were treated as received and have the suffix "C" appended to the specimen number. The remaining half were labeled using the standard LC method where an identification is laser engraved within the flat area of the CD between the center hole and the stacking ring. This half has the suffix "D" appended to the serial number. Attempts were made to have the "C" and "D" versions of the same manufacturer and time frame.

The discs were divided into five groups according to the distribution of Table 1 below:

Disc ID	Number *	Temperature (˚C)	Relative Humidity (%)
1 through 30	30	60	85
31 through 45	15	70	85
46 through 60	15	80	55
61 through 70	10	80	70
71 through 80	10	80	85

- The total number of discs per Temperature and Relative Humidity stress is actually twice the number listed in table 1, as the "C" and "D" versions were combined for test purposes.

Discs were tested according to the test protocol of the Datarius XXXXX test. All parameters were recorded and considered. For the purposes of this report, the ten second average block error rate (BLER) was used to indicate the rate deterioration of the specimen. This is in accordance with the ANSI/NAPM IT9.21-1996 document.

Testing was performed prior to the disc receiving any accelerated stress and according to planned scheduled below. Contingencies that arose during testing necessitated modifications that were taken into account for life estimation.

Temperature (˚C)	Relative Humidity (%)	Interval (Hours)
60	85	1000 hrs
70	85	750 hrs
80	55	500 hrs
80	70	500 hrs
80	85	500 hrs

The test parameters for each individual disc at each individual test interval is shown in Attachment 1.

By measuring the BLER as a function of time (hours) the rate of change of BLER as a function of temperature and relative humidity can easily be determined by linear regression. This regression produces an equation of the form:

$$\text{BLER}(t) = \text{Rate} \times \text{Time (hours)} + \text{Intercept}$$

By substituting 220 as the recognized BLER at end of life into the above equation, the time to reach this value is readily obtained. The time is equivalent to the estimated service life and was determined for each disc in the study on an individual basis. This produced 160 opportunities for EOL estimates including both the "C" and "D" versions of tested media.

Due to a variety of reasons, some of the calculated values were rejected and the discs not included in this study. Reasons include:

- Maximum recordable BLER achieved prior to the first test interval
- Maximum BLER obtained on consecutive test intervals.
- Assignable cause for exclusion.

Due to the exclusions from reasons listed above the final number of specimens used in the ultimate calculations was reduced from the 160 entrants to 111 final specimens analyzed. The larges block of exclusions were those from the 80 ˚C / 70% RH test condition explained below.

Data Analysis:

The estimated time to reach end-or-life (EOL) for each disc within a stress condition, (temperature / relative humidity chamber) was compared to four standard distributions. These include the Weibull, Lognormal, Exponential and Normal distributions. These four are considered to be the most common mathematical estimate of a population based on a sample treated to accelerated stress condition.

Below are shown the comparisons for each distribution and for each stress condition. Table 3 summarizes the list of Figures used for this comparison.

Table 3: Summary of Figures comparing distribution techniques

Figure	Temperature (˚C)	Relative Humidity (%)
1	80	85
2	80	70
3	80	55
4	70	85
5	60	85

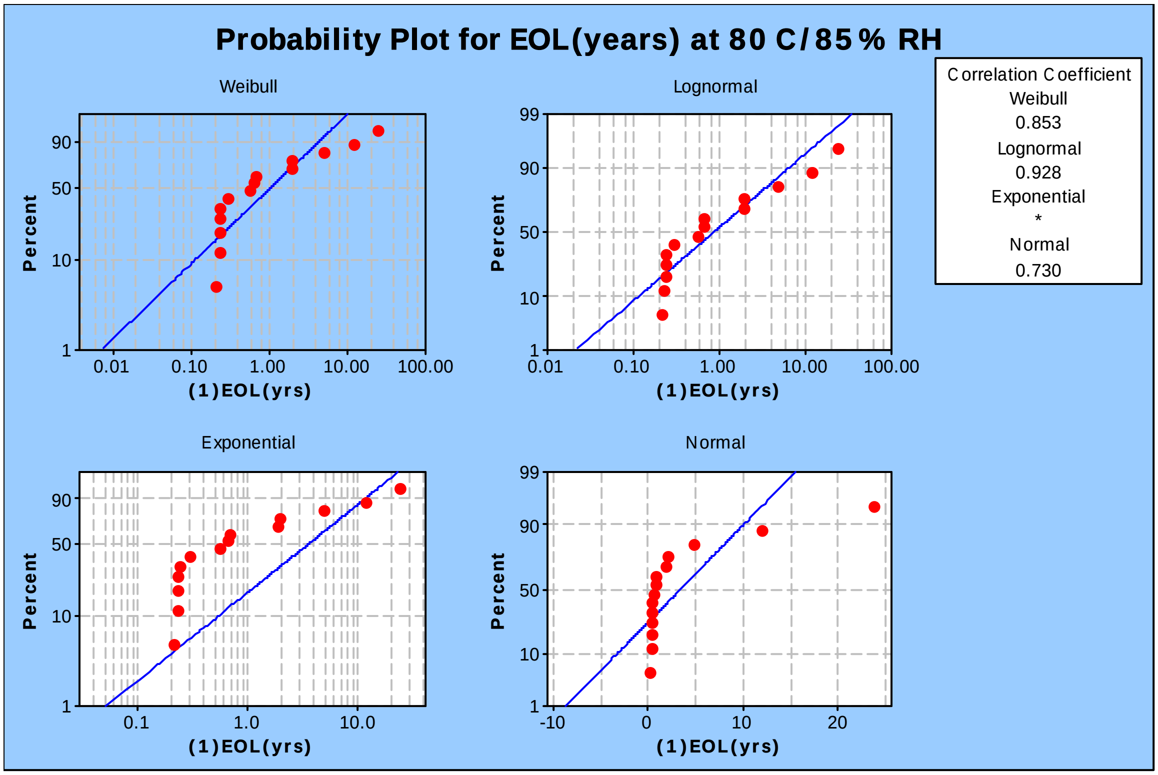

Figure 1: Comparison of Distribution Estimate for 80 ˚C / 85% RH

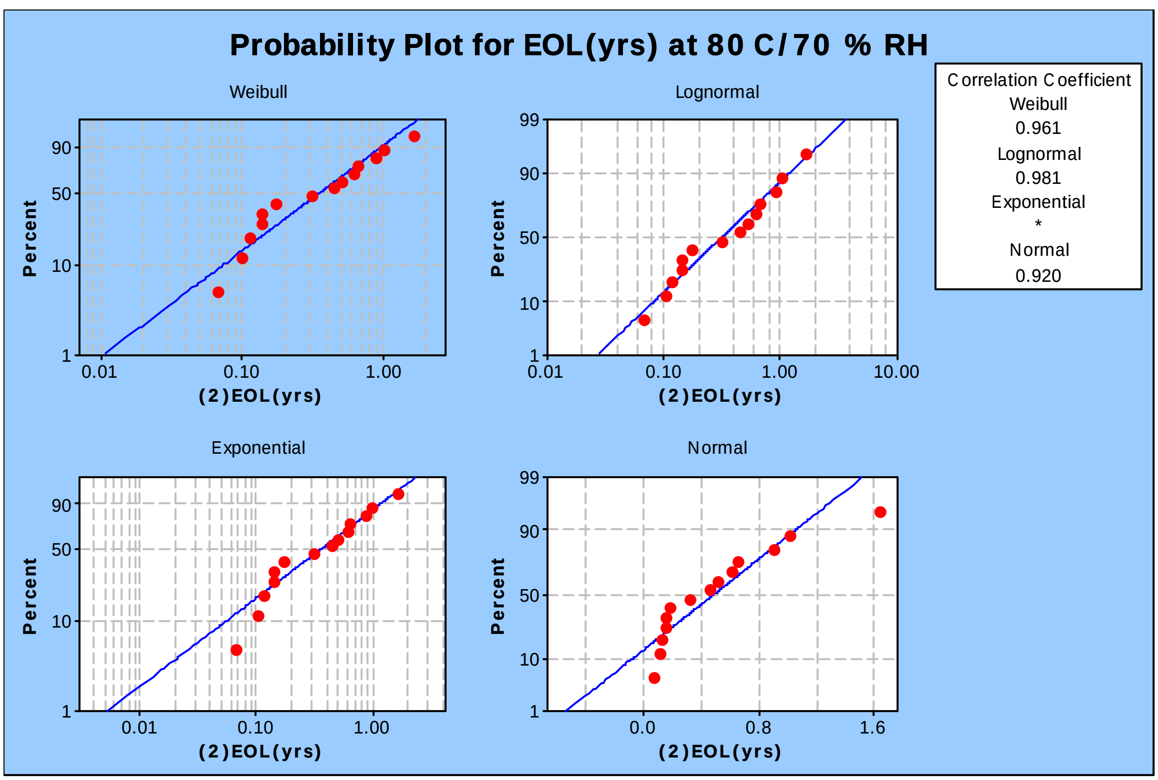

Figure 2: Comparison of Distribution Estimate for 80 ˚C / 70% RH

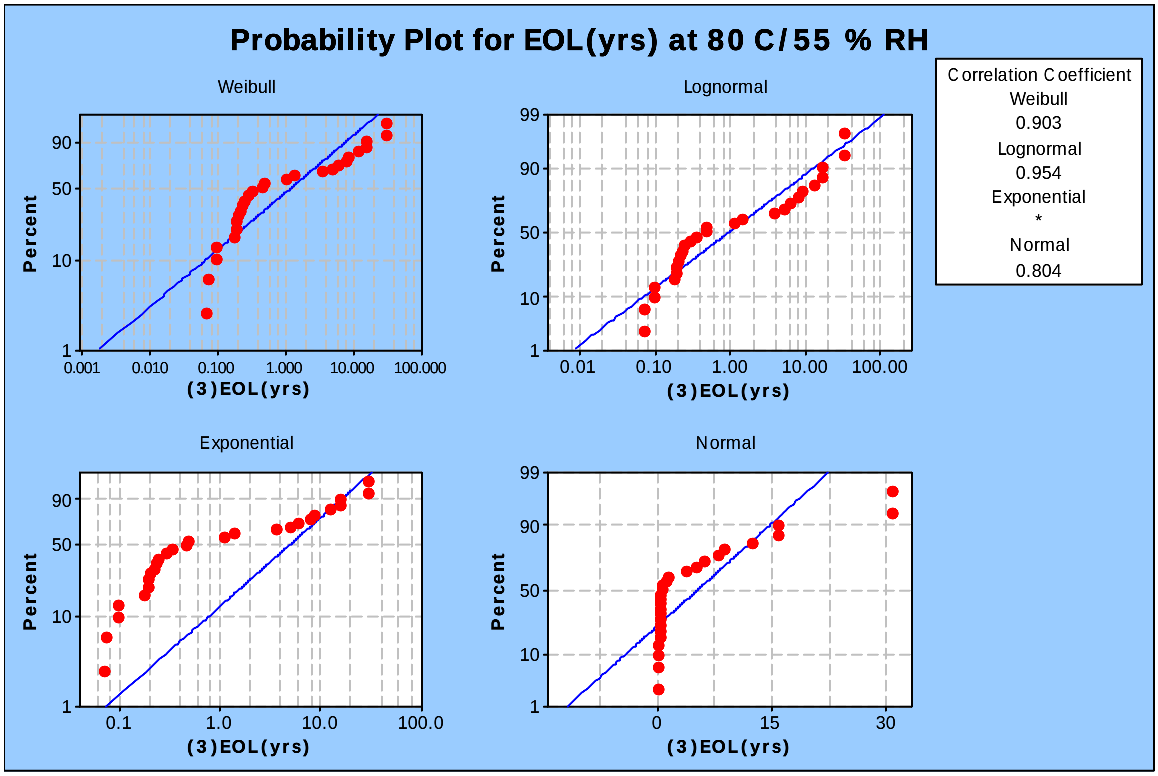

Figure 3: Comparison of Distribution Estimate for 80 ˚C / 55% RH

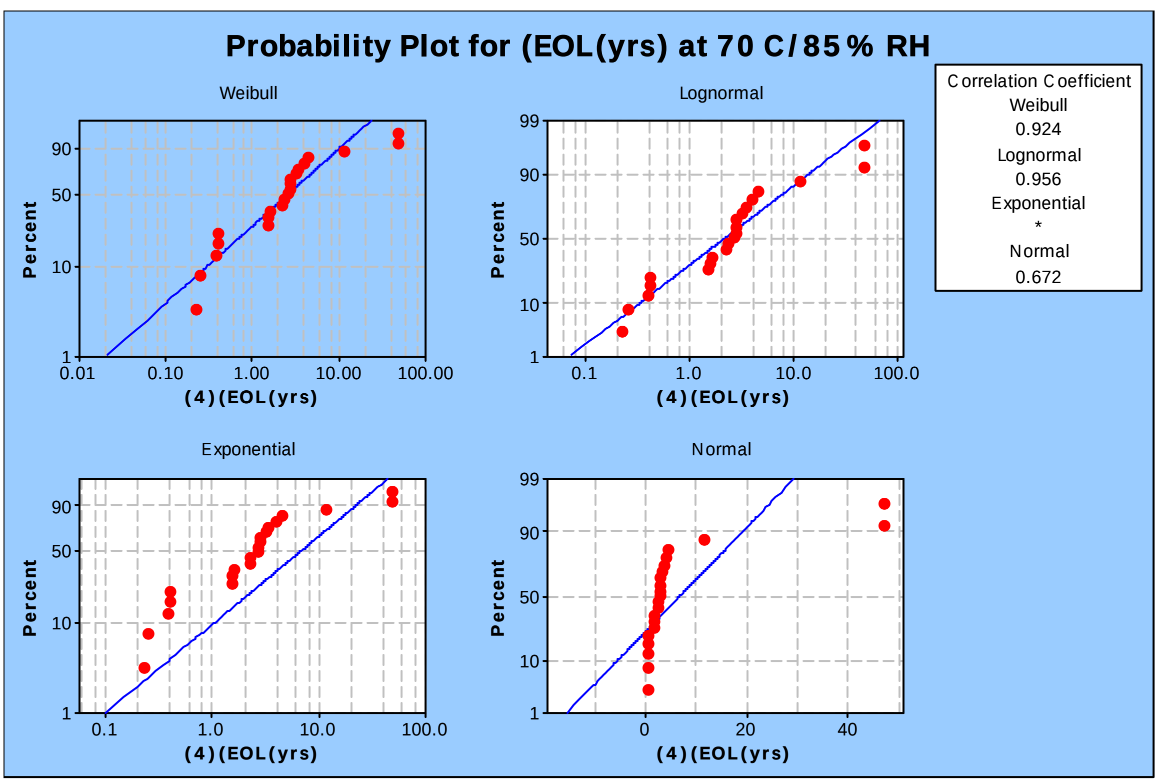

Figure 4: Comparison of Distribution Estimate for 70 ˚C / 85% RH

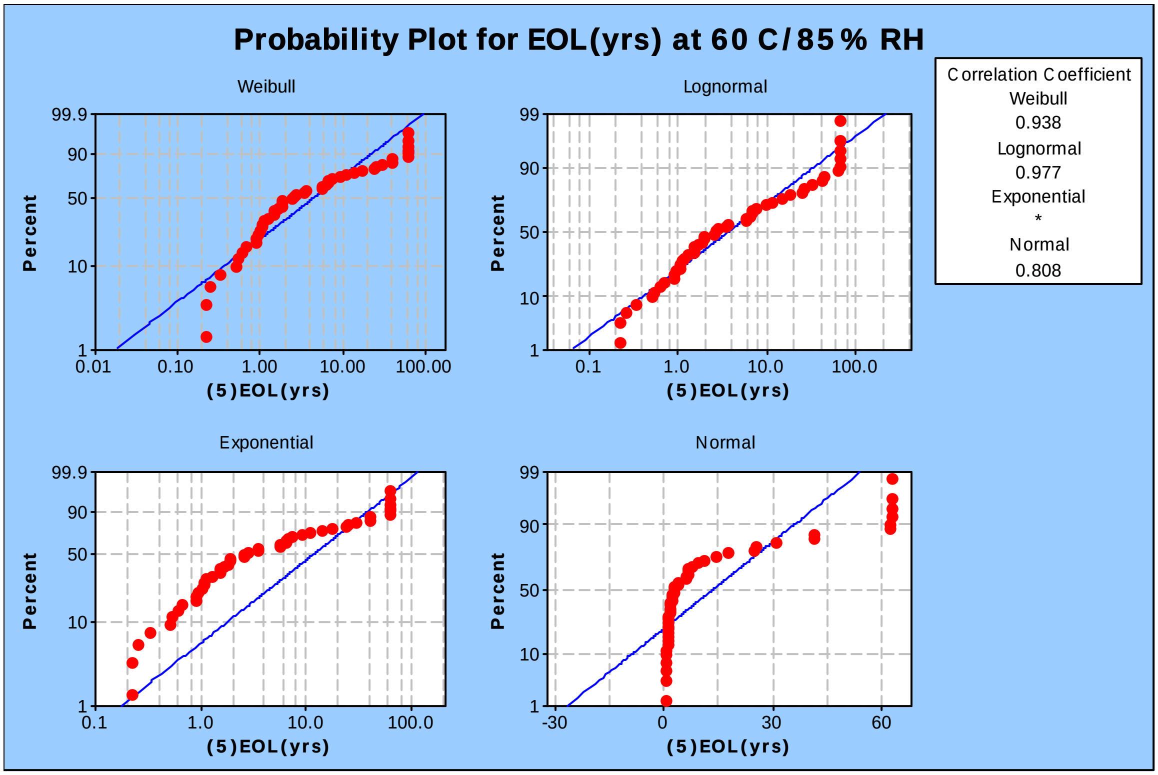

Figure 5: Comparison of Distribution Estimate for 60 ˚C / 85% RH

Table 4 below summarizes the regression coefficient for each stress the Weibull, Lognormal and Normal distribution technique for comparison. The correlation for the exponential distribution is made graphically.

Stress	Weibull	Lognormal	Normal
80 ˚C/85% RH	.853	.928	.730
80 ˚C/70% RH	.961	.981	.920
80 ˚C/55% RH	.903	.954	.804
70 ˚C/85% RH	.921	.956	.672
60 ˚C/85% RH	.938	.977	.808

The higher the correlation coefficient, the better the fit of the experimental data to the estimated distribution. A correlation of 1.00 indicates a perfect fit. It may be seen that, as expected, both the Weibull and the lognormal distribution provide an acceptable fit to the experimental data. In each case, the lognormal distribution was the best fit and was chosen for further analysis in favor of the Weibull distribution.

Figures 6 through 10 show the fit and distribution parameters of the experimental data to the Lognormal distribution: Table 5 summarizes the Figures shown.

Table 5: Summary of Lognormal Distribution Figures shown below.

Figure	Temperature (˚C)	Relative Humidity (%)
6	80	85
7	80	70
8	80	55
4	70	85
10	60	85

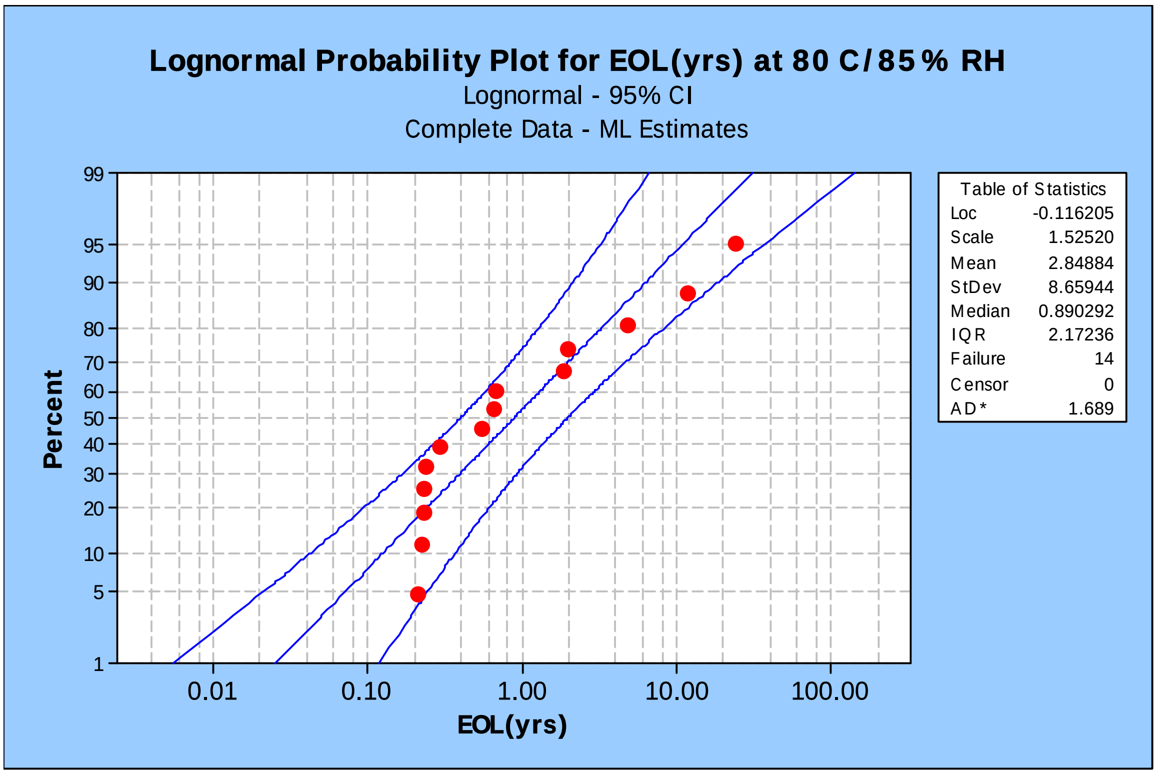

Figure 6. Lognormal Probability Plot for 80 ˚C/85 % RH

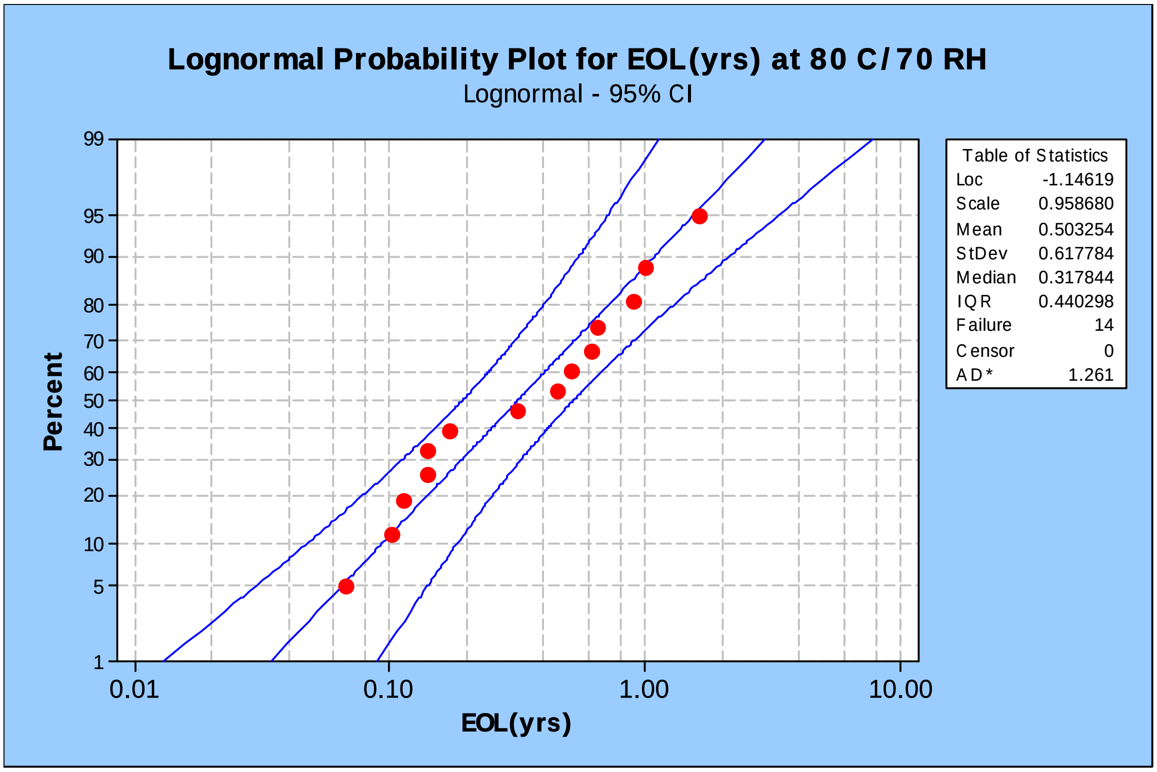

Figure 7. Lognormal Probability Plot for 80 ˚C/70 % RH

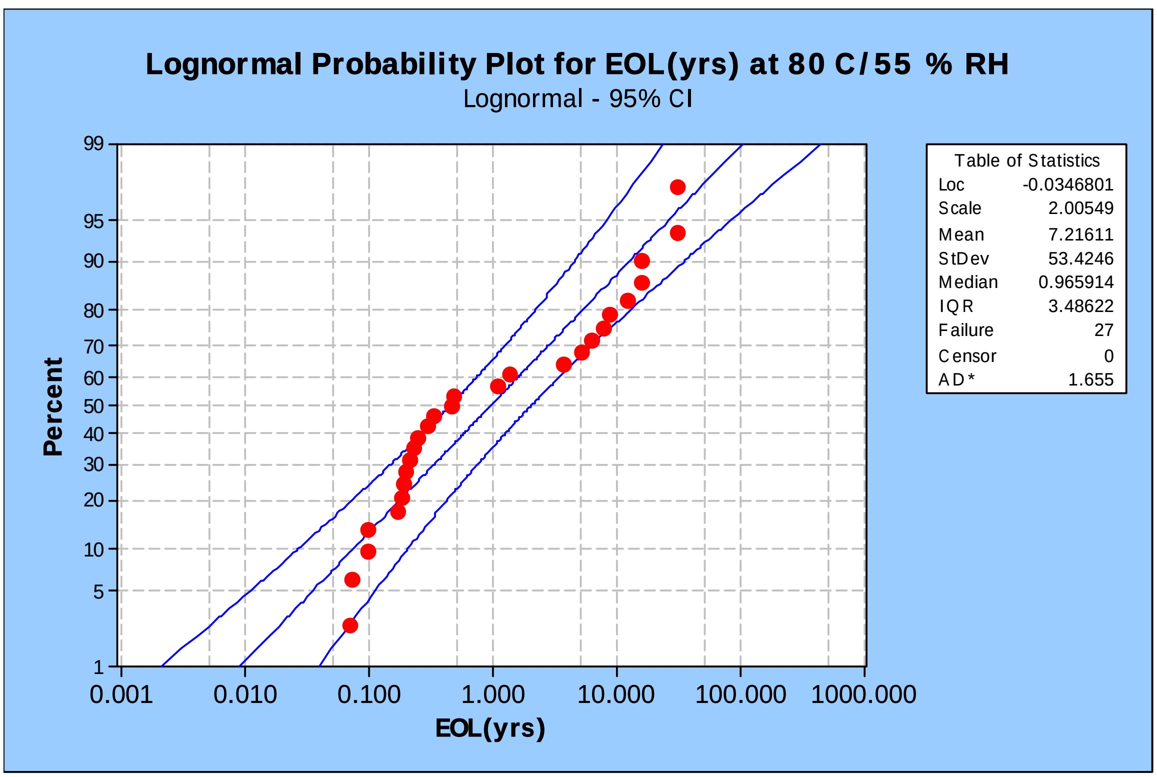

Figure 8. Lognormal Probability Plot for 80 ˚C/55 % RH

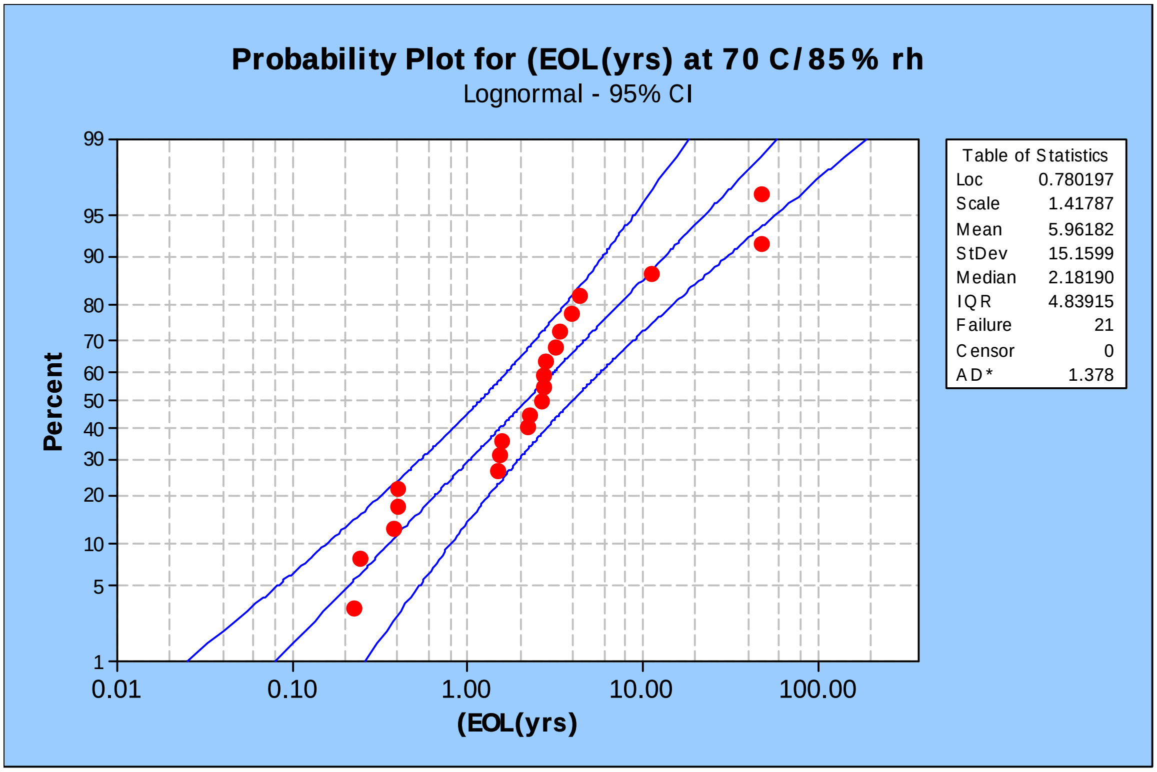

Figure 9. Lognormal Probability Plot for 70 ˚C/85 % RH

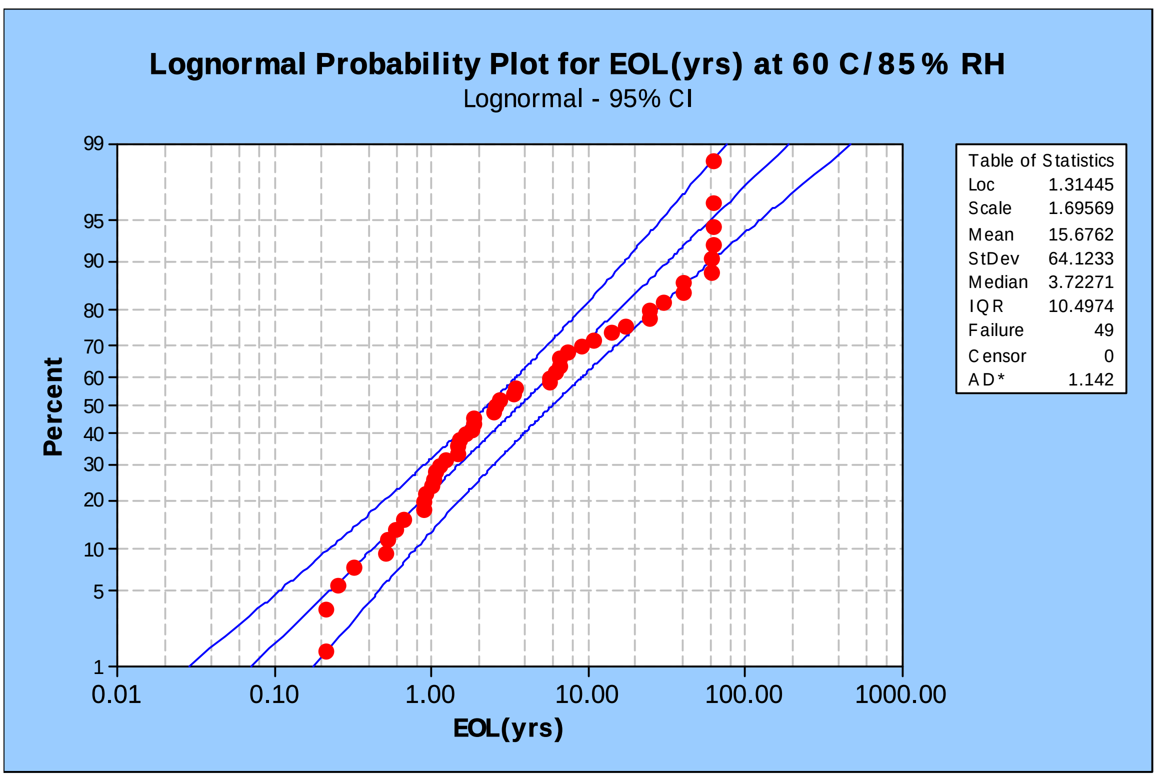

Figure 10. Lognormal Probability Plot for 60 ˚C/85 % RH

At this point of the analysis, a table was prepared of the mean of the end-of-life versus the temperature and relative humidity at which the disc was stressed. This information is summarized in Table 6 below:

Table 5: Summary of Lognormal Distribution Figures shown below.

Mean (EOL) (yrs)	Temperature (˚C)	Relative Humidity (%)
2.8488	80	85
0.5032	80	70
7.2161	80	55
5.9618	70	85
15.676	60	85

It may be see that the Mean EOL for the 80 ˚C/70% RH is out f line with the other stress levels. This is counter intuitive. Discussions with the test analyst and the recorded notes in the summary sheets indicate that the probability of early EOL values may be the effect of a malfunction of the stress chamber. As the minimum requirements for solving the Eyring equation may be met without these EOL estimates, they were excluded from further consideration.

Acceleration Factors:

As specified in the ANSI test procedure ANSI/NAPM IT9.21-1996, a reduced form of the Eyring acceleration model was used to relate EOL, Temperature and Relative Humidity. The Equation:

$$Time_{End-ofLife} = Ae^{\Delta H/kT}e^{(B)RH}$$

was solved by converting it to a linear model:

Log(Time) = A + ΔH/kT +B(RH)
Where   ΔH = Activation Energy
K = Boltzman's Constant
T = Temperature (Kelvin)
B = pre-exponential factor for relative humidity
RH = Relative Humidity expressed as a fraction.

With four experimental equations, and only three unknowns, the Eyring equation may be solved. The solution yields:
A = -24.7
ΔH/k = 10038
B = -3.2

Substituting the values for 1/T (k) and RH corresponding to 25 ˚C and 50% RH produces an estimated Log(mean) of 7.37. This corresponds to a mean life time of 1592. years for CD-ROMs stored at 25 ˚C and 50% RH.

To obtain the distribution for these discs, the mean time to fail at 25 ˚C / 50% RH is divided by the mean time to fail at each of the accelerated conditions. By knowing this ratio, the relative acceleration may be assigned to each of the stress conditions. The results of this operation are shown in Table 6 below.

Table 5: Summary of Lognormal Distribution Figures shown below.

Temperature (˚C)	Relative Humidity (%)	Mean (EOL) (yrs)	Acceleration Factor
80	85	2.8488	563
80	70	0.5032	Not Used
80	55	7.2161	222
70	85	5.9618	268
60	85	15.676	102

The acceleration factors are used to normalize the EOL times at the accelerated condition to the EOL estimated had the stress been at 25 ˚C/50% RH. This is accomplished by multiplying the EOL times measures in an accelerated stress by the acceleration factor for that stress. In this manner, all of the measured values are normalized to the 25 ˚C/50% RH and may be combined into one data set. Once this is done, the combined data is again analyzed for its distribution characteristics. The results of this are shown in Figure 11 below.

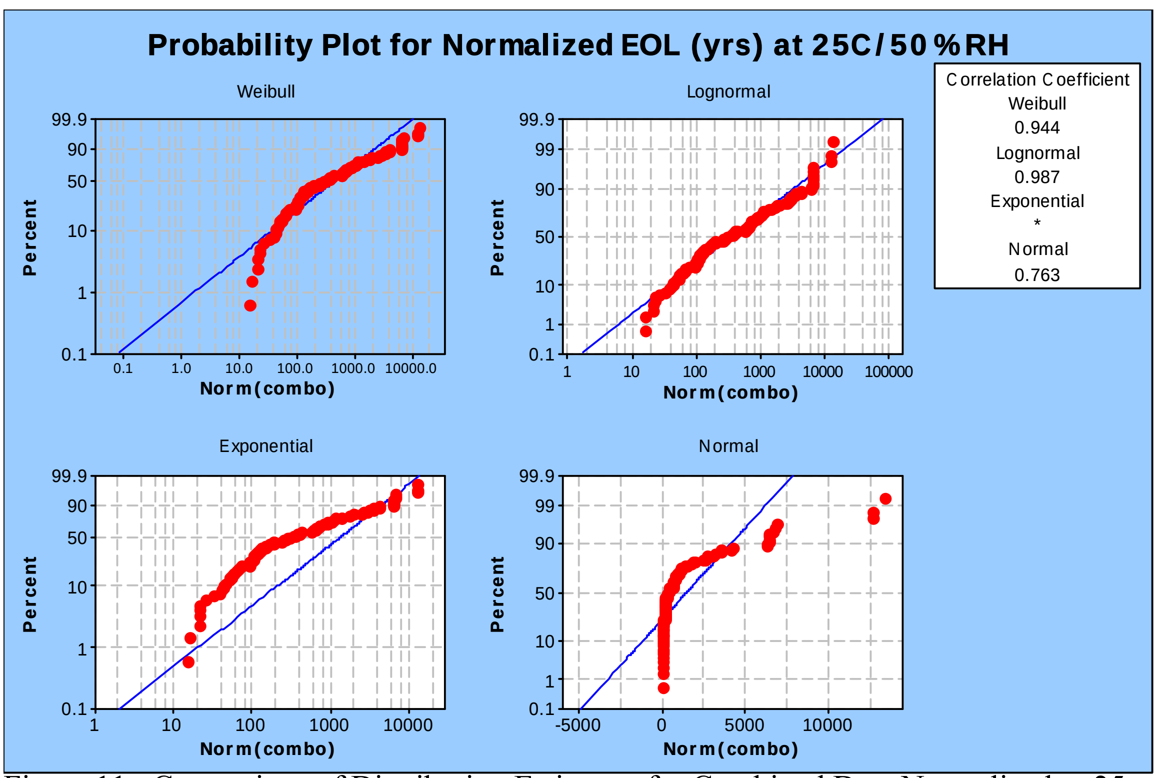

Figure 11: Comparison of Distribution Estimates for Combined Data Normalized to 25 ˚C and 50 % RH

Again, the lognormal distribution is slightly better fit than the Weibull, with a correlation of 0.987. This is an indication of an excellent fit to the data.

Figure 12 below is a more detailed graph of the probability of failure as a function of time, using the lognormal distribution of the Combined Data Normalized to 25 ˚C and 50 % RH.

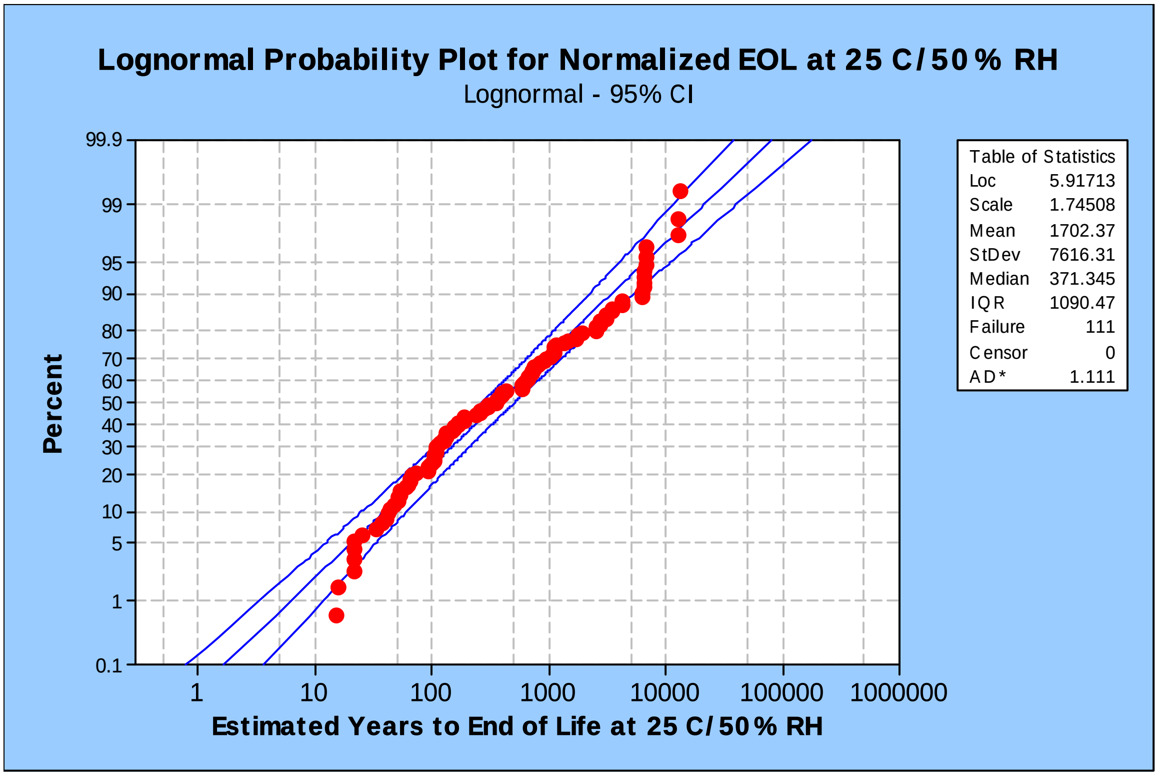

Fig 12: Lognormal Probability Plot of Combined Data Normalized to 25 ˚C / 50 % RH.

This same data may be replotted using a linear axis to show the probability of failure. Figure 13 below is a Cumulative Failure Plot of the Combined Data Normalized to 25 ˚C / 50 % RH. It indicates the percent of the total discs that are estimated to have failed, by the age of the disc.

Figure 14 below is the same graph as Figure 13 but with a scale chosen to more clearly indicate the percent failures expected during the first 200 years.

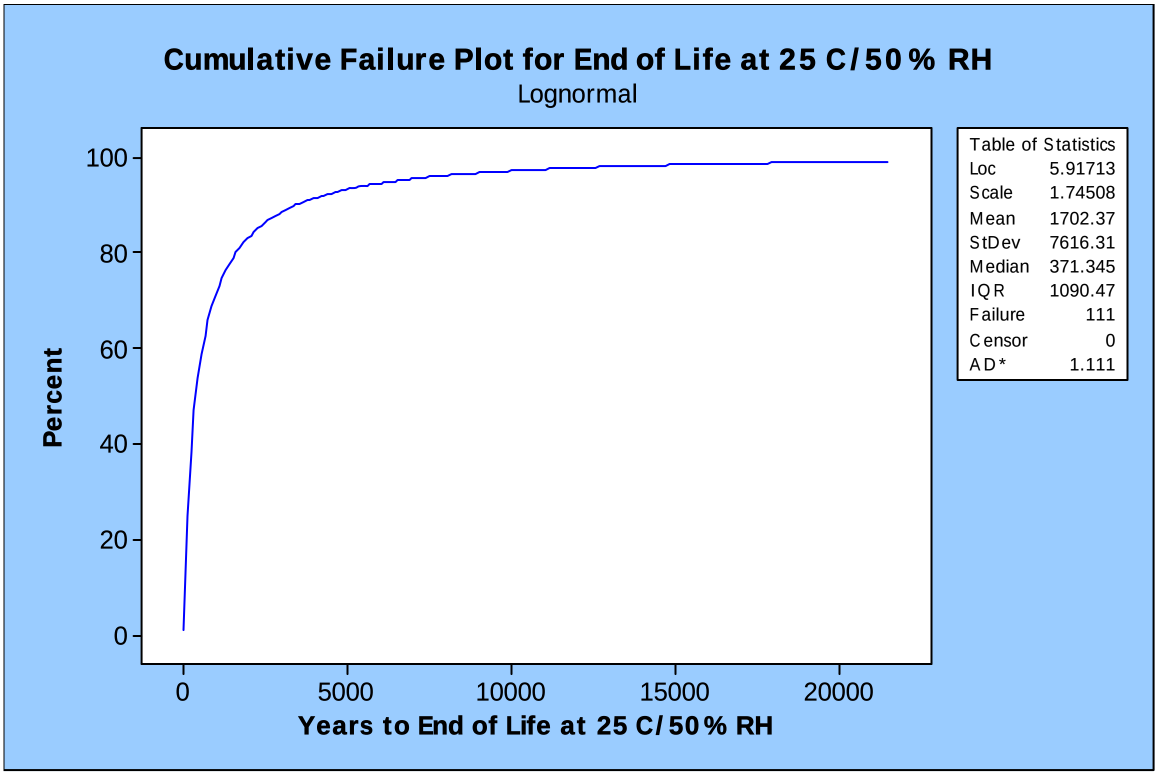

Figure 13: Cumulative Failure Plot for Combined Data Normalized to 25 ˚C / 50 % RH.

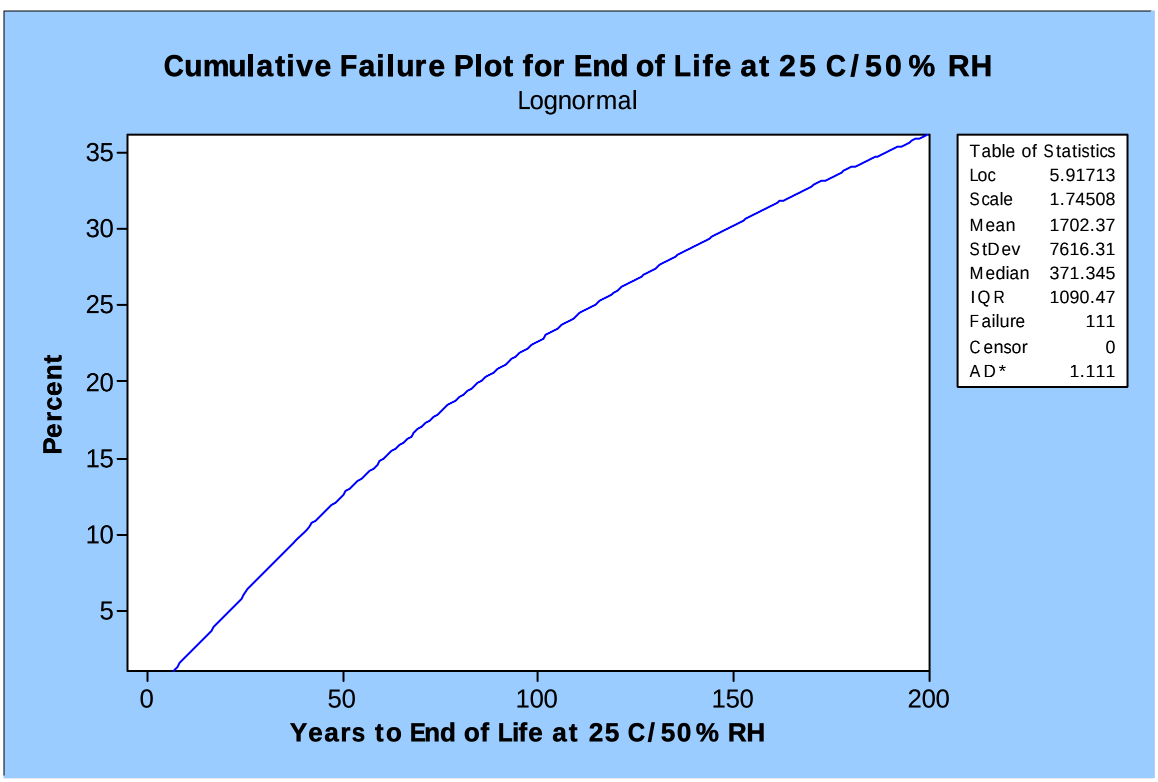

Figure 14: Cumulative Failure Plot for Combined Data Normalized to 25 ˚C / 50 % RH

Table 6 below summarizes the failure probabilities after some select periods of time.

Table 6: Cumulative Failure Percent by years of age

Time (Years)	Cumulative Percent Failing.
1	0.03
5	0.68
10	1.92
20	4.71
25	6.1
50	12.53
75	17.97
100	22.61
150	30.17
200	36.14